様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

平成 ２９ 年　 ６ 月　 ２ 日現在

機関番号：８２４０１
研究種目：若手研究(B)
研究期間：2014～2016
課題番号：２６７９０００８

研究課題名（和文）Hybrid Superconductor - Ge/Si core/shell nanowire devices

研究課題名（英文）Hybrid Superconductor - Ge/Si core/shell nanowire devices

研究代表者

ディーコン　ラッセル（Deacon, Russell）

国立研究開発法人理化学研究所・石橋極微デバイス工学研究室・研究員

研究者番号：４０５５２４４３

交付決定額（研究期間全体）：（直接経費）　　3,200,000円

研究成果の概要（和文）：Ge/Siコアシェルナノワイアにおけるスピン軌道相互作用について調べ、電界である程度制御可能であり、電界制御型スピントロニクスデバイスやマヨラナ粒子を実現するために十分大きいことが分かった。また、大きな臨界磁場を有する超伝導金属を使って接触抵抗の小さな電極を形成する技術を確立した。マヨラナ粒子の検出に向け、交流ジョセフソン効果を測定するシステムを構築した。よくわかっているトポロジカル絶縁体であるHgTeを使った初期的な実験で、マヨラナモードに起因する４π周期の電流位相特性を示唆する超伝導電流を観測した。

研究成果の概要（英文）：We study the spin orbit interaction in Ge/Si core/shell nanowires and identify short electrically tunable spin orbit lengths suitable for spin based electronic devices and the realization of Majorana Fermions. We develop techniques to produce transparent contacts to Ge/Si nanowires using high magnetic critical field superconductors. Toward the detection of Majorana Fermions we develop a measurement system to study the ac-Josephson effect in topological Josephson junction. Initial studies were performed on the well established HgTe based topological insulator system in which we detect evidence for a 4-pi periodic supercurrent expected for Majorana modes.

研究分野：固体物理

キーワード：超伝導

１．研究開始当初の背景

At the time of application Ge/Si core/shell nanowires had been proposed as a strong candidate system for spin manipulation and as a platform for the study of Majorana Fermions. Among the predicted desirable characteristics are:

(1) The lack of ionizing dopants leading to high mobility devices.
(2) Hole states which are sensitive to confinement and are confirmed to have long spin lifetimes.
(3) A predominance of spin-zero nuclei which suppresses the hyperfine interaction and is predicted to result in long spin coherence times.
(4) It is proposed that hole states in Ge/Si core/shell nanowires exhibit a strong ‘direct’ Rashba Spin Orbit Interaction which arises from dipole coupling to internal electric fields.

Majorana Fermions had been studied in the tunneling spectroscopy of InAs and InSb nanowires coupled to superconducting contacts. However more detailed proof of the properties of the Majorana, such as 4π periodicity of Majorana bound states, remained to be confirmed.

２．研究の目的

Our research goals were divided into three targets.

(1) Study of spin physics in Ge/Si nanowires to reveal details of the spin-orbit interaction, a key ingredient for recipes to realize Majorana Fermions.

(2) Development of techniques to produce clean Ge/Si nanowire devices with superconducting contacts.

(3) Detection of Majorana Fermions using Josephson junction dynamics probed via the ac-Josephson effect and application of this technique to the Ge/Si nanowire system.

３．研究の方法

(1) We develop fabrication methods to transfer single nanowires with micron scale precision onto prefabricated gates allowing the creation of complex devices. This method utilizes polymer stamps to pickup/transfer target materials and can be used both with semiconductor nanowires (InAs, InSb and Ge/Si core/shell wires) and layered 2D materials such as Graphene or hexagonal boron nitride. Ge/Si core/shell nanowires were supplied by Prof. Lieber, Harvard University, USA.

(2) We developed methods to contact Ge/Si core/shell nanowires with high critical field superconductors suitable for the realization of Majorana Fermions using sputtering, dry and wet etching and rapid thermal annealing.

(3) We characterize the spin-orbit interaction in Ge/Si nanowires using weak anti-localization measurements in devices equipped with paired top and bottom gates allowing control of carrier density and asymmetry of the confinement field. We later attempt to utilize the spin-orbit interaction to couple electronic spin states to photons in microwave resonators for circuit quantum electrodynamics studies.

(4) We develop methods to detect Majorana Fermions by measuring the dynamics of the supercurrent in Josephson junctions using the ac-Josephson effect. Josephson junctions formed from a topological

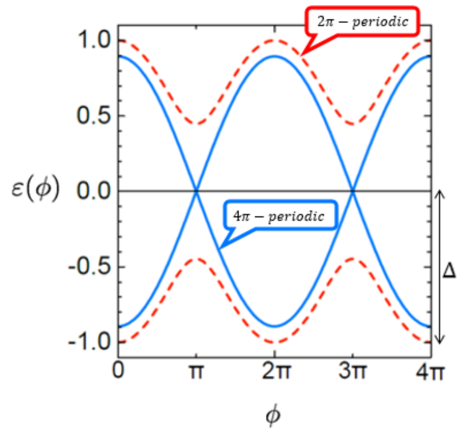

Fig. 1. Illustration of Andreev bound states expected in a topological superconducting Josephson junction. Majorana bound states (blue) possess a topologically protected crossing when superconducting phase difference is equal to π, resulting in a 4π periodicity. In contrast conventional Andreev bound states (red) are typically gapped and have a 2π periodicity. Here only a single conventional mode is drawn but a large number of modes may be present with only one or two Majorana modes dependent on the geometry of the system.

superconductor (fabricated from nanowires or topological insulators with superconducting contacts) are predicted to exhibit topologically protected zero crossing Andreev bound states which are the Majorana states of the system. The Majorana bound state exhibits a 4π periodicity with superconducting phase difference across the junction in contrast to the 2π periodicity expected for conventional Andreev bound states, Fig. 1. The Majorana bound state can be revealed through measurement of the Shapiro response of the system in which the junction dynamics are phase locked to an external ac-current drive. The presence of a 4π periodic mode is confirmed by observation of Shapiro steps in the junction voltage which are double the value expected for conventional 2π periodic modes. In addition, a measurement of the Josephson emission from the junction will reveal a peak in emission spectrum at half the Josephson frequency.

４．研究成果

(1) Precision alignment system for single nanowires

We develop a micron-scale alignment system for the pick-up and positioning of single nanowires onto prefabricated gate structures or into complex circuits such as microwave resonators. The technique utilizes a home-made alignment system and the pickup and transfer of nanowires using fine indium wire probes or polymer stamps. This alignment technique has been applied to all of the nanowire studies associated with this project being suitable for alignment of InSb, InAs, Ge/Si nanowires as well as multiwalled carbon nanotubes. Examples of devices fabricated with this system can be seen in the figures in following sections.

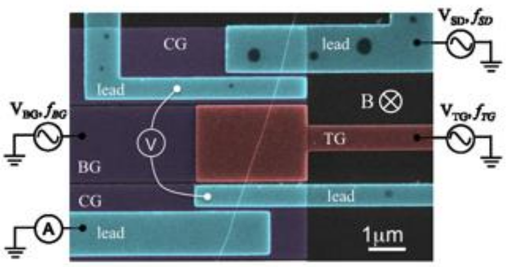

Fig. 2. Example of a single Ge/Si core/shell nanowire contacted with Palladium leads and gated with back-gate (purple) and a top-gate (red). Hafnium oxide is used as a gate dielectric.

(2) Weak anti-localization measurements

We fabricate devices with single Ge/Si core/shell nanowires positioned onto surface gates with thin Hafnium dielectric and capped with a top-gate electrode, Fig. 2. The combined back and top-gates allow control of the symmetry of the internal electric field of the nanowire to tune the strength of the electric dipole spin-orbit interaction. Measurement of the weak-antilocalization (Fig. 3) allows evaluation of device parameters including the spin-orbit length, the distance of travel over which the hole spin will rotate by 2π. Our measurements indicate an electrically tunable spin-orbit length in the range 4-8 nm with a spin-orbit energy almost an order of magnitude larger than observed in InSb or InAs nanowire systems, providing a strong indication for the presence of the predicted dipole direct Rashba spin orbit interaction [manuscript submitted]. This promising result motivated us to attempt coupling of the hole states of the nanowire to microwave photons in superconducting resonator cavities.

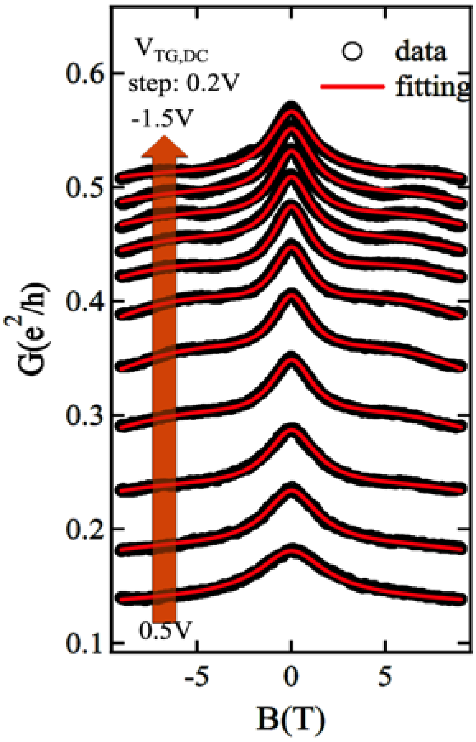

Fig. 3. Differential conductance as a function of magnetic field B for a range of gate conditions. The peak at zero bias indicates weak anti-localization which is suppressed with increasing field. Red lines are a best fit to a theoretical model used to extract device parameters.

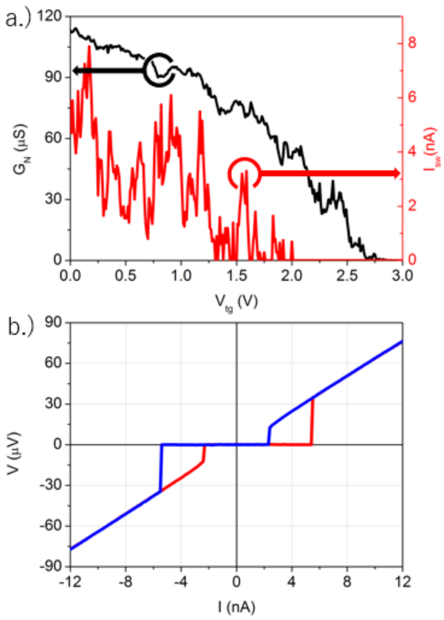

Fig. 4. (a) Gate tunable normal state conductance of a Ge/Si nanowire contacted with MoRe. We observe pinch-off behavior with increasing top-gate voltage (V_{tg}) indicating hole states. In addition we measure a gate tunable superconducting switching current, I_{sw}. (b) An example of the supercurrent measured under current bias for V_{tg}=0V.

(3) <u>Transparent superconducting contacts to Ge/Si core/shell nanowires</u>

We develop a method to produce transparent superconducting contacts to Ge/Si core/shell nanowires using first wet etching in diluted HF and KOH to strip oxide of the outer Si shell followed by deposition of Molybdenum-Rhenium (MoRe 50/50% by weight) from a sputter target. The resulting device is then rapidly thermal annealed (at 280-300 degrees) for approximately 15 seconds in a forming gas to diffuse the MoRe through the Si shell contacting the core. MoRe was found to be a robust against thermal processes which degrade the quality and interfaces of other high critical magnetic field superconductors (such as Nb, NbTIN and NbN). In addition, our MoRe deposition system was found to produce excellent contacts to hBN encapsulated Graphene devices (Amet *et al.*, Science 352, 6288 [2016]). An example of the superconducting transport of a MoRe contacted Ge/Si nanowire device is shown in Fig. 4.

(4) <u>Coupling of Ge/Si nanowires to microwave resonators for circuit QED</u>

Based on the successful measurement of short spin-orbit lengths we aim to utilize this characteristic to couple hole spins in Ge/Si nanowires with the electric field of a photon confined in a superconducting coplanar waveguide cavity. Resonator devices were fabricated using precise alignment of the single Ge/Si core/shell nanowires onto 100nm pitch gates used to for double quantum dots. Hexagonal Boron nitride was used as a gate dielectric as it is a clean single crystal that is free of charge traps that in Hafnium or silicon nitride dielectrics adversely affect the device performance. An example device is shown in Fig. 5.

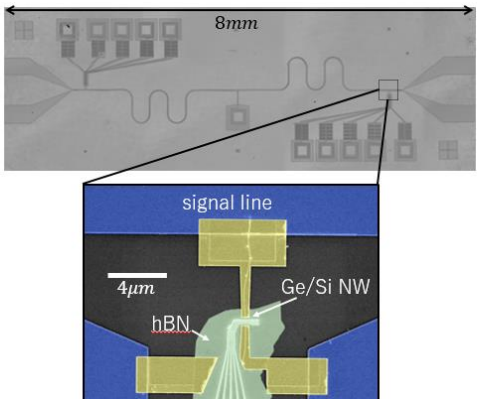

Fig. 5. Example of a Ge/Si core/shell nanowire double quantum dot coupled to a MoRe superconducting coplanar waveguide resonator. The nanowire is precisely aligned onto five prefabricated 100nm pitch gates covered with hexagonal boron nitride as a clean gate dielectric.

We succeed to perform dissipative readout of charge states using the cavity coupled nanowire devices. Example results are shown in Fig. 6. The cavity resonance is centered at 5.9677 GHz and has a Q-factor of approximately 6000. In Fig 6 (a) and (b) we probe the cavity at the center frequency and simultaneously detect both the current through the double quantum dot and the phase of the cavity transmission. We observe a clear honeycomb structure indicating the double quantum dot charge stability diagram (red lines in Fig. 6 (a)) which is reflected in the phase response. From fitting of the response with the Jaynes Cummings model we evaluate charge dipole coupling rates as high as 85 MHz but charge decoherence rates of 10s of GHz indicating operation in the dispersive regime [manuscript in preparation]. Similar measurements were initially performed using the more established InSb nanowire devices and published [Wang *et al.*, APL 108, 203502 (2016)]. Finally, by

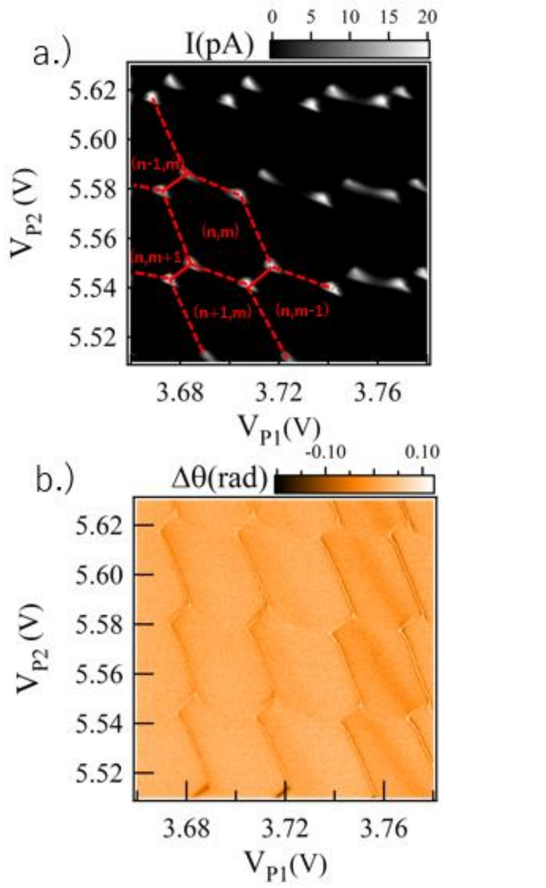

Fig. 6. (a) Measurement of double quantum dot stability diagram for holes states as a function of two plunger gates. (b) Measurement of resonator phase.

fabricating resonators from NbTiN we were able to extend the operation of our cavities to high magnetic fields (exceeding 2 Tesla), opening the possibility to in the future study the coupling of Zeeman split spin states coupled to the cavity field through the spin-orbit interaction, a topic we are currently continuing to follow.

(5) Development of system for detection of Majorana Fermions through Josephson junction dynamics

We develop a measurement system installed on a He3/He4 dilution refrigerator which combines cryogenic microwave techniques and homemade microwave filtered DC lines to probe the ac-Josephson effect in our devices. Initial measurements were conducted on HgTe topological insulator Josephson junctions in collaboration with the group or Prof. Molenkamp, University Würzburg, Germany. We identify clear evidence for a 4π periodic supercurrent contribution in junctions made from strained HgTe 3-dimensional topological insulators and HgTe quantum spin hall insulators. Initially we identify doubling of the Shapiro step voltage for suitably low frequency rf-drive as illustrated for the Quantum spin hall insulator system in Fig. 7. A conventional Josephson junction exhibits Shapiro steps at voltages V=nhf/2e, where f is the drive frequency and index (n∈ℤ) We observe the disappearance of odd n index steps indicating the presence of a 4π periodic supercurrent. Furthermore, from application of the Resistively Shunted Junction (RSJ) model we are able to estimate the relative contribution of 4π and 2π periodic modes and we find values consistent with the expectation of single modes on each edge of the device. The techniques employed for the detection of 4π periodic modes are also applicable to the nanowire based Majorana devices. However, at present attempts to identify Majorana modes in nanowire devices remain inconclusively and are complicated by the small critical currents when exposed to the large magnetic fields required to access the Majorana Fermion regime.

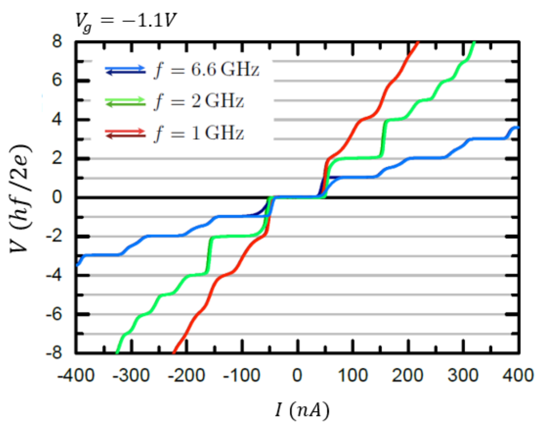

Fig. 7. Example of Shapiro response measured in a Quantum spin hall insulator Josephson junction. For low rf-drive frequencies we observe a clear doubling of the Shapiro step voltages which can be seen as missing steps for odd indexes of the junction bias in units of hf/2e.

５．主な発表論文等

（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計　７　件）

① R.S. Deacon*, J. Wiedenmann*, E. Bocquillon*, F. Domínguez, T.M. Klapwijk, P. Leubner, C. Brüne, E.M. Hankiewicz, S. Tarucha, K. Ishibashi, H. Buhmann, and L. W.

Molenkamp, "Josephson radiation from gapless Andreev bound states in HgTe-based topological junctions", Physical Review X 7, 021011, 1-7 (2017) (査読有) (* indicated equal contribution).
DOI:10.1103/PhysRevX.7.021011

② F. Dominguez, O. Kashuba, E. Bocquillon, J. Wiedenmann, R.S. Deacon, T.M. Klapwijk, G. Platero, L.W. Molenkamp, B. Rauzettel, and E.M. Hankiewicz. "Josephson junction dynamics in the presence of 2π-4π periodic supercurrents", Physical Review B 95, 195430-195439 (2017). (査読有) DOI:10.1103/PhysRevB.95.195430

③ E. Bocquillon*, R.S. Deacon*, J. Wiedenmann*, P. Leubner, T.M. Klapwijk, C. Brüne, K. Ishibashi, H. Buhmann, and L.W. Molenkamp, "Gapless Andreev bound states in the quantum spin Hall insulator HgTe", Nature Nanotechnology 12, 137-143 (2017). (査読有) (* indicated equal contribution)
DOI:10.1038/nnano.2016.159

④ J. Weidenmann*, E. Bocquillon*, R.S. Deacon*, S. Hartinger, O. Herrmann, T.M. Klapwijk, L. Maier, C. Ames, C. Brune, C. Gould, A. Oiwa, K. Ishibashi, S. Tarucha, H. Buhmann, L.W. Molenkamp. "4π-periodic Josephson supercurrent in HgTe-based topological Josephson junctions", Nature Communications 7, 10303, 1-7 (2016). (査読有) (* indicated equal contribution)
DOI:10.1038/ncomms10303

⑤ F. Amet, C. T. Ke, I. V. Borzenets, J. Wang, K. Watanabe, T. Taniguchi, R. S. Deacon, M. Yamamoto, Y. Bomze, S. Tarucha, and G. Finkelstein, "Supercurrent in the quantum Hall regime", Science 352, 6288, 966-969 (2016). (査読有)
DOI:10.1126/science.aad6203

⑥ R. Wang, R. S. Deacon, D. Car, E. P. A. M. Bakkers, and K. Ishibashi "InSb nanowire double quantum dots coupled to a superconducting microwave cavity", Appl. Phys. Lett. 108, 203502-203504 (2016). (査読有)
DOI:10.1063/1.4950764

⑦ S. Baba, J. Sailer, R.S. Deacon, A. Oiwa, K. Shibata, K. Hirakawa, and S. Tarucha, " Superconducting transport in single and parallel double InAs quantum dot Josephson junctions with Nb based superconducting electrodes", , Appl. Phys. Lett. 107, 222602-222604 (2015). (査読有)
DOI:10.1063/1.4936888

〔学会発表〕(計 5 件)

① "Signatures of 4π periodicity in the dynamics of HgTe Josephson Junctions", International symposium on revolutionary atomic-layer materials, Tokyo Electron House of Creativity, Tohoku University, Sendai, Japan. October 21st, 2016. R.S. Deacon.

② "Gapless Andreev Bound States in HgTe topological Josephson junctions", International Symposium on Dynamics in Artifical Quantum Systems, Research Center for Advanced Science and Technology, Tokyo University, Japan. January 12th 2016. R.S. Deacon.

③ "Anomalous Shapiro steps in strained HgTe Josephson junctions", 1st Annual symposium of Topological Materials Science, Shiran Kaikan, Kyoto University, Japan. December 13th 2015. R.S. Deacon.

④ "Zero-energy Andreev bound states in a HgTe topological Josephson junction", ISNTT2015, NTT, Atsugi, Japan. November 18th 2015. R.S. Deacon.

⑤ "Non-local spin entangled states in double quantum dot Josephson Junctions", TFC-Workshop on Quantum Nanostructures and Electron-Nuclear Spin Interactions, Tokyo Electron House of Creativity, Tohoku University, Sendai, Japan. October 20th 2015. R.S. Deacon.

６．研究組織
(1)研究代表者
ディーコン　ラッセル　(RUSSELL DEACON)
国立研究開発法人理化学研究所・石橋極微デバイス工学研究室・研究員

研究者番号：４０５５２４４３